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AN INTELLIGENT VOLTAGE CONTROL SYSTEM FOR KOREAN POWER SYSTEMS

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Abstract
This paper presents an intelligent reactive power and voltage control system that has been developed over three years in Korea. The general structure and more importantly the least cost search method for a feasible solution are discussed herein. As a result, the system has shown a promising performance and will therefore be tested on Jeju Island, Korea as a part of the smart grid demonstration system.

Keywords: Voltage and reactive power control, intelligent control, least cost search

1. Introduction

Recently, massive blackouts in Europe and North America have occurred, caused by imbalances in their reactive power. In this situation, the reactive power losses have been increased due to the installation of long-distance transmission lines, since the power plants are located far from the load-demand regions. This is a critical problem that many countries are facing these days. Therefore, appropriate voltage and reactive power control needs to be implemented that will contribute in preventing massive blackouts and reduce reactive power losses.

In recent years, the Korean power system has been operated more closely to its stability limits because of a rapid growth in the load-demand, as can also be seen in Europe. Specifically, the voltage stability problem in the metropolitan regions caused by the northward power flow limits in the Korean power system is regarded as one of the critical issues to be addressed for improving the power system operational efficiency and stability. Unfortunately, the voltage and reactive power maintenance is only done by individual substations, since it is not easy to secure a site for voltage compensation equipment; the regional systematic voltage control framework is not yet prepared. Therefore, real countermeasures against blackouts or equipment damage caused by a voltage collapse need to be taken, as it is highly probable for such events to happen in the Korean power system.

Many papers have been written regarding voltage control. However, these papers have not dealt with an intelligent voltage and reactive power control in Korea. In the 1970s, expert systems using heuristic knowledge utilizing computer simulations emerged in step with artificial intelligence. An expert system for real-time voltage and reactive power control was proposed based on the sensitivity tree in Canada [1]. In Spain [2, 4, 7], voltage control systems were successfully applied in the Spanish power system. In addition, several advanced countries are operating voltage and reactive power control systems by taking into account the inherent characteristics of their individual power systems [5, 6].

In this paper, we develop and simulate an intelligent control system that provides voltage and reactive power control for Jeju Island in the Korean power system. This system makes full use of a sensitivity matrix, a numerical analysis technique for control equipment to monitor and idealize such things as the generator terminal voltage, the shunt capacitors, and the transformer taps, as well as to perform least cost searches that use sensitivity coefficients as the cost function, leading to the development of an intelligent control system.

2. The Modeling of the Voltage Control Problem

Assuming an N bus power system with M control actions, the relationship between the bus voltages and the control actions can be represented as shown in Figure 1. It should be noted that each control action has a significant impact on the voltages in several buses. For a particular voltage violation, it is possible to select the control action needed to remove this voltage violation.

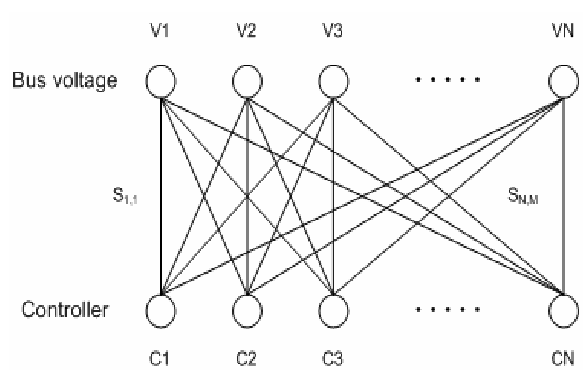

Figure 1: Relationship of the bus voltages and control actions

This paper deals with the above-mentioned causal relationship between the bus voltage and the control action by using state-space representation.

Figure 2 shows a sample of the state space of N load buses and the M controller system.

As shown in Figure 2, V_i is the bus voltage with the largest deviation. The relationship between the bus voltage and the control action is presented as a sensitivity value in the branches and the other bus voltages using this control action are illustrated in the third step. If the voltage violation still exists and the voltage deviation of V_K is the largest, the control at the second stage is executed, starting from vertex V_K. In this manner, the voltage control problem is reduced to a simple path detection, which finds the path to reach the steady state starting from the bus with the abnormal voltage.

3. The Intelligent Voltage Control System

3.1 The Voltage Control System Structure

The structure of the intelligent voltage and reactive power control system is shown in Figure 3. The intelligent control system is made up of a numerical module based on the sensitivity matrix and a knowledge base which is made up of a wide variety of information related to the power system status and the control knowledge.

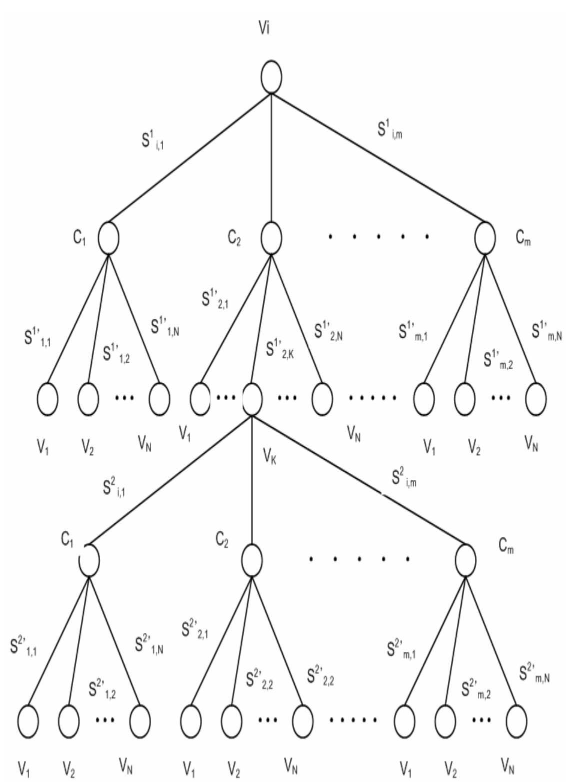

Figure 2: The voltage control state-space model

3.2 The Sensitivity Matrix

The sensitivity technique is one of the numerical methods used for the analysis of the linear system. The sensitivity matrix is the fundamental parameter for the intelligent voltage control system. It describes the relationship between the bus voltages with respect to the amount of compensation that is injected into the generator terminal voltage, the shunt capacitors, and the transformer tap.

The sensitivity matrix is established by the relationship between the voltage and the reactive power. Assuming that the voltage angle is negligible in the Jacobian matrix, the relationship between the voltage and the reactive power is encapsulated by:

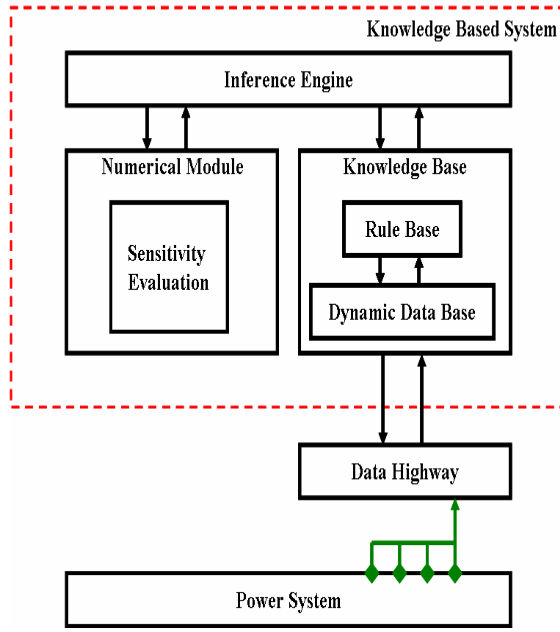

Figure 3: The structure of the intelligent voltage control system

$$[\Delta V] = \left[\frac{\partial Q}{\partial V}\right]^{-1} [\Delta Q] \qquad (1)$$

The sensitivity matrix is presented by the control actions as:

$$\begin{aligned} &\circ\, \Delta V_i = S_{sh} \bullet \Delta U_{sh} \\ &\circ\, \Delta V_i = S_{Vg} \bullet \Delta U_{Vg} \\ &\circ\, \Delta V_i = S_T \bullet \Delta U_T \end{aligned} \qquad (2)$$

ΔV_i : the voltage change at the i bus

S_{sh}, S_{Vg}, S_T: the sensitivity matrix of the compensation devices

ΔU_{sh},ΔU_{Vg},ΔU_T: quantity changes of the compensation devices

3.3 The Knowledge Base

The knowledge in a specific problem domain is classified by the truth and the rule and then stored in the database and the rule base, respectively. The database is divided into a static database and a dynamic database. These databases are composed of the immutable truth in a specific domain or the hypothetical truth derived from the inference process.

The knowledge base stores the system information obtained from the load flow and uses it for both search and inference. The major database and the rule base are composed as follows:

(A) The Database

□ The load bus voltage profile calculated from the load flow

□ The open/closed status of the transmission lines

□ The upper and lower value limits of each bus voltage and control device

④ The upper and lower limit of the voltage regulation

⑤ The priority of the compensation devices

⑥ The sensitivities of the bus voltages with respect to each control device

(B) The Rule Base

① Check the voltage violation

○ Abnormal voltage [p.u.] : 0.95 < V or V > 1.05

② Check the control limits of the generator terminal voltage

○ 0.95 ≤ upper and lower limits of generator terminal voltage [p.u.] ≤ 1.05

③ Establish the sensitivity tree for each abnormal bus voltage

④ Find the most effective control for the bus with the worst voltage violation

⑤ Calculate the control value needed to remove the voltage violation

⑥ Select the control actions and estimate the voltage variations

4. The Case Study

4.1 Using PSCAD/EMTDC

In order to verify the intelligent control system, a case study for the Jeju power system in Korea was carried out using PSCAD/EMTDC. In this case, the upper and lower limits of an abnormal bus voltage are specified at 0.977~1.023 pu and the limits of the voltage regulation are specified at 0.99 ~1.01 pu. In addition, the primary compensation device was selected to be the generator terminal voltages. For the transmission line outage occurring between the Hanra (190) bus and the Seongsan (200) bus, the voltage violations happened at Seongsan (200) bus, as can be seen in Table 1. The system recognized that an abnormal bus voltage occurred, and then output the control action signal seen in Table 2 in order to adjust the Seongsan (200) bus voltage to be within the voltage regulation parameters.

As shown in Table 2, the intelligent control system applied three processes to the generator terminal voltage in order to adjust the Seongsan (200) bus voltage.

Table 1: The Voltage Profile of the Busses in the Case of a Transmission Line Outage

Bus Number	Bus Name	Voltage[p.u.]
120	North Jeju TP	1.002544
121	North Jeju CS	1.002545
122	North Jeju TS	1.002545
130	East Jeju	1.001748
140	New Jeju	0.998798
150	Hanrim CC	1.010965
160	Andeok	1.002576
170	South Jeju TP	1.003147
180	New Seogwi	0.989196
190	Hanra	0.99071
200	**Seongsan**	**0.973214**
210	Pyoseon	0.990717
220	Sanji	1.001457
330	Hanrim	1.008834
350	Jochen	0.980627

As shown in Figure 4, the intelligent control system adjusted the abnormal bus voltage to be within the voltage regulation parameters without causing another abnormal bus voltage.

Table 2: The Control Action

Bus Number	Compensation Devices	Control quantity [p.u.]
20122	North Jeju TP Gen. terminal voltage	+ 0.05
20123	North Jeju CS Gen. terminal voltage	+ 0.016667
20124	North Jeju TS Gen. terminal voltage	+ 0.016667

Figure 4 shows the voltage profile of the control action before and after the fault.

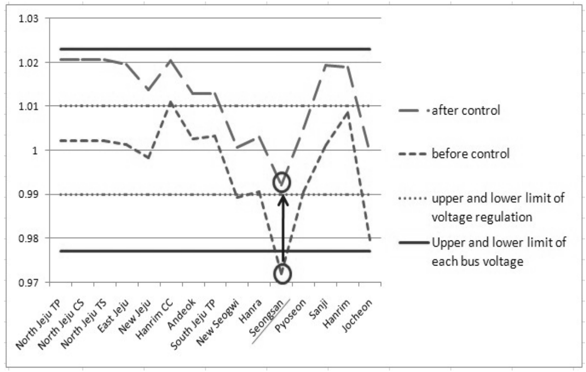

Figure 4: The voltage profile

4.2 Using the RTDS

In order to verify the real-time performance of the intelligent voltage control system, a case study for the Jeju power system in Korea was carried out using a RTDS (Real Time Digital Simulator).

(A) The Interface

Figure 5 shows the HMI display of the intelligent voltage control systems. The operating conditions for the intelligent voltage control system can be set on the HMI.

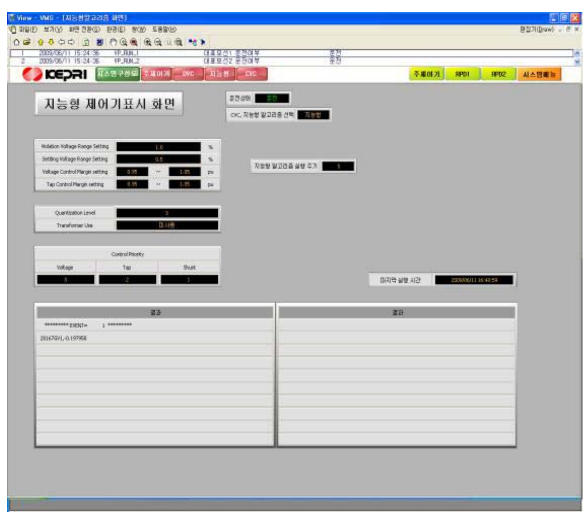

Figure 5: The HMI display of the developed system

The adjustable system operation parameters are as follows:

① The upper/lower limits of the abnormal bus voltage

The user can specify a wide abnormal voltage range to be applied

② The upper/lower limits of the voltage regulation

This value does not adjust the control action within the upper/lower limits of the abnormal voltage but calculates the control action within the upper/lower voltage regulation limits for the buses having abnormal voltages.

③ The upper/lower limits of the generator terminal voltage

The intelligent voltage control system adjusts the bus voltage using a generator terminal voltage within this setting range

④ The compensation device priority

For an effective and efficient voltage-control a user may set the control devices to be used in a specific order (i.e. the generator terminal voltage, then the shunt capacitor, then the transformer tap)

⑤ The controller execution cycle

Because of the controller doesn't execute during a transient state, the controller execution cycle setting is an important issue

(B) The Case Study

In this case study, we found an abnormal bus voltage in the case of a transmission line outage on Jeju Island using the RTDS. However in this case, thetransmission line outage occurred in the North Jeju TP(120) bus and the East Jeju(130) bus)

The system operating conditions were as follows:

① The upper/lower limit of abnormal bus voltage [p.u.]
: 0.95 < V or V > 1.05

② The upper/lower limit of the voltage regulation [p.u.]
: 1.03 > V > 0.97

③ The generator terminal voltage [p.u.]
: 0.95 ≤ generator terminal voltage ≤ 1.05

④ the priority of the voltage control devices
: Generator >shunt capacitor> transformer tap

⑤ The system execution cycle
: 30 [step] (about 90[sec])

Table 3 shows the bus voltage profile before the control action.

Table 3: The Voltage Profile before the Control Action

BUS NO.	BUS NAME	First control before	Second control before	Final control before
120	North Jeju TP	1.051344	1.058798	1.04125
121	North Jeju CS	1.051343	1.058797	1.04125
122	North Jeju TS	1.051343	1.058797	1.04125
130	East Jeju	0.941803	0.971353	1.040724
140	New Jeju	0.9623	0.991398	1.041826
150	Hanrim CC	0.999744	1.025911	1.058213
160	Andeok	1.008411	1.038311	1.061596
170	South Jeju TP	1.013565	1.045016	1.066134
180	New Seogwi	1.005808	1.029971	1.045863
190	Hanra	1.01381	1.033414	1.04169
200	Seongsan	1.019621	1.033073	1.029228
210	Sanji	0.941176	0.97075	1.040172
220	Jochen	1.037213	1.04742	1.036721
230	Hanrim	1.000012	1.02677	1.058658

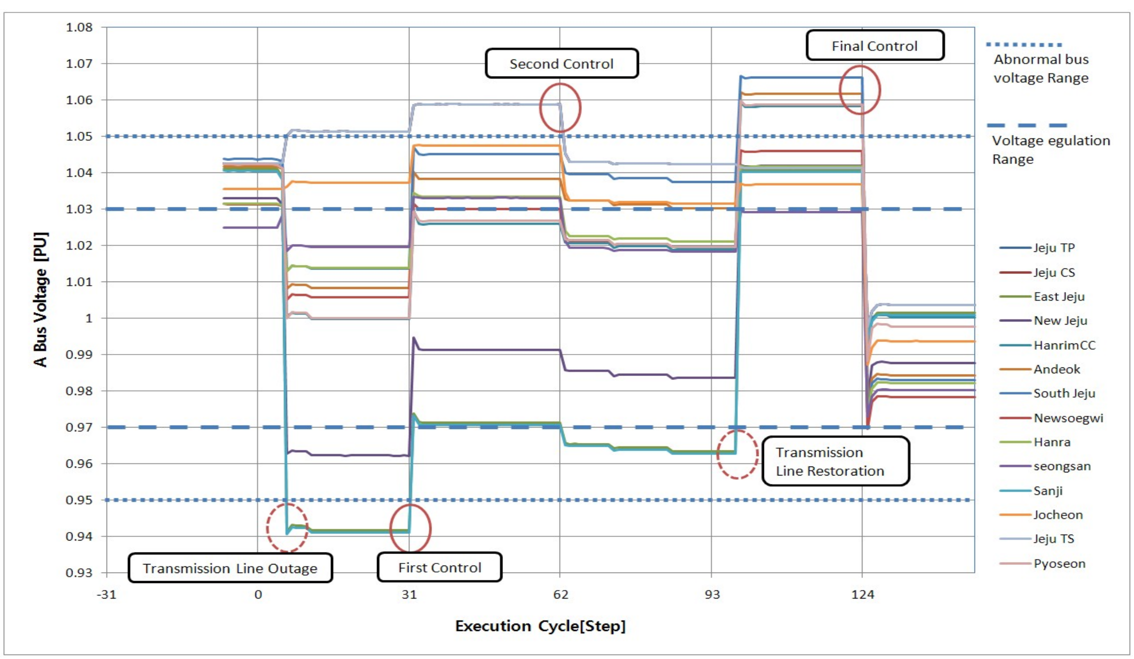

Figure 6: The 154kV bus voltage profile in the Jeju power system

Figure 6 shows the voltage profile according to the control action. Looking at Figure 6, the voltage violation happened in several buses after a transmission line outage. The system performed the voltage control based on the largest abnormal bus voltage (Sanji (210)).

After the voltage control, the Sanji (210) bus was adjusted to be within the voltage regulation parameters. However, another voltage violation happened on the North Jeju TP (170) bus. The system then performed another voltage control during the next system execution cycle. The North Jeju TP (170) bus voltage could not be adjusted to be within the voltage regulation parameters.

The reason the system did not have new voltage violations in another bus were due to the linear prediction of the system.

Finally, a voltage violation happened at the South Jeju bus (170) after the transmission line was restored. The system adjusted all of the bus voltages to be within the voltage regulation parameters at the next system execution cycle.

5. Conclusions

In this paper, an intelligent control system integrated with a numerical based analysis program and an intelligent program has been developed. The numerical based analysis program is coded, using the C language, based on a sensitivity matrix predicting the load bus voltage variations by the monitoring of voltage control devices, such as the generator terminal voltage, the shunt capacitors, and the transformer tap. The rule base and the inference engine for the voltage and the reactive power control were developed on the basis of a sensitivity tree that is fairly connected to the load bus voltage and the control actions. The intelligent program has been formulated using PROLOG employing an inductive rule base combined with a numerical and logical computation method.

The performance of the proposed intelligent control system has been verified using data from Jeju Island by dynamic simulation using PSCAD/EMTDC. The real-time performance of the system has been tested using RTDS. The performance results of the PSCAD/EMTDC simulation and the RTDS testing are satisfying. In the next step, the system will be tested in the Jeju island power system as a part of the smart grid demonstration system

Acknowledgement

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